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Review

Measuring economic performance, social progress and sustainability using an index

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ABSTRACT

The energy crisis and a greater awareness among the general public regarding the issue of climate change have, between them, led to a notable increase in the interest shown by governments in relation to the problem of environmental sustainability. An example has been the initiative taken by the President of France to set up a commission, known as the Sarkozy Commission, named after the President, bringing together renowned economists to study and propose forms of economic performance measurement related to social progress. This article aims to propose a methodology to establish a quantitative definition of sustainability structured on the principles of minimum and maximum entropy production, and, based on this, outline a way of organizing the many sources of, and kinds of energy, we have available to us in order of the intensity of their respective environmental impacts. Based on this, we could produce an *Environmental Sustainability Index*, linked to existing statistical indicators of human development, and thereby arrive at a *Sustainable Human Development Index*, which would be positively or negatively influenced by parameters linked to environmental sustainability and quality of life. In order to ensure that this index can produce practical results, the WTO (World Trade Organization) would have to establish a scale of increments, to be applied to export tariffs on products originating in countries with different indexes.

Contents

1. Introduction

The notion of sustainable development used internationally is based on the so-called *Brundtland Report*, of 1987, also entitled “*Our Common Future*”, which defined sustainable development as one that satisfies our own present-day needs, without jeopardizing the capacity of future generations to satisfy their needs [1]. This definition is adequate for use in political and diplomatic discourse, but it does not go far enough in allowing us to list, in order of the magnitude of their environmental impacts, different projects or undertakings with a common objective in mind.

Before establishing this relationship, one should first highlight three categories of sustainability, which are *economic* sustainability, *social* sustainability and *environmental* sustainability [2].

Classical economists in general (and some natural scientists) rarely make a distinction between these different categories because they believe that technology has the power to transform natural resources into various forms of capital, and that economic science has the tools to ensure that technology and market forces are always able to transform natural capital into man-made capital (roads, factories, industrial and agricultural production, etc.). They group land, mineral resources, the capacity of the environment to recycle waste, the labour force and the previously mentioned man-made capital within a homogenous package – capital, in short. To these economists, sustainability means maintaining the purchasing power of capital and its profitability, regardless of any limitations

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placed upon it by the finitude of our planet's natural resources. This view represents a form of *weak sustainability*.

Political and social scientists consider sustainability as the cohesion of society in the face of common goals, society's participation in the democratic process, governability and access by the population to education, food, health services, etc.

A definition of *environmental* sustainability (and sustainable economic performance) puts quantitative, physical restrictions, as it implies limiting the supply of energy and raw materials to reserves of natural resources, and to the capacity of the environment to absorb and recycle the waste that is generated.

There are areas where economic sustainability overlaps with social sustainability, but clearly both ultimately depend on environmental sustainability, which, consequently, must be considered as our priority.

2. GDP as an indicator of sustainable economic performance and social progress

Until recently, GDP was considered the most relevant indicator of economic performance and social progress [3]. However, due to the energy crisis, and, principally, to climate change, we have witnessed an increase in interest among governments in relation to the problem of environmental sustainability. A notable example has been the initiative taken by the President of France to set up a commission (the Sarkozy Commision), to bring together renowned economists to study and propose forms of economic performance measurement related to social progress [4].

It is already generally recognized that GDP confuses a quantitive concept, that of *growth*, with a qualitative concept, that of *development*, and one can note that the concept of "sustainable growth" is an oxymoron, this because capital made by man does not substitute natural capital, and we cannot have sustainability that is above the resilience of nature in order to reconstitute reserves of natural resources [2].

On the other hand, one can see that the market, on its own, does not have the conditions to limit the supply of energy to the reserves of natural resources, and to the capacity of the environment to absorb and recycle the waste that is generated. This is why growth has to be contained within a state of equilibrium [3], especially as development does not necessarily depend on growth, but rather on other factors such as improved education, better products, maintenance of infrastructure, rationalization of transport systems, etc., with priority given to the quality of life of society as a whole.

Incidentally, it was nearly half a century ago that Rumanian economist, Nicholas Georgescu-Roegen laid the foundations of an ecologically and socially sustainable economic theory [5].

The effective compatibility of the growth of the use of natural resources, with the capacity of the environment to renew them and recycle waste, is an essential condition for sustainability. And we cannot hope that the market, alone, will create the necessary conditions for this compatibility. In order to achieve this, one should proceed with a decoupling between economic growth and the use of natural resources, so that production remains limited to reserves of natural resources, and by the capacity of the environment to reconstitute these natural resources and to recycle the waste that is generated [6].

The present models of development are based on unlimited growth and are seriously flawed in decoupling the profitability or returns of the economy from the value of natural resources and labour. A consequence of this has been the proliferation of financial assets, which have provoked the present global economic crisis. In fact, "The global financial stockpile (total of bank deposits, private debt notes, government debt and shareholdings) rose from US$10 trillion in 1980 (close to the value of global GDP at that time), to US$167 trillion in 2006 (nearly four times global GDP today). In 2006 alone, global financial assets increased by US$25 trillion, or almost 18% (growth three times greater than GDP), led by increases in the value of assets in the United States (US$5.7 trillion) and China (US$2.8 trillion). In the meantime, currency reserves of governments increased from US$910 billion in 1990 to US$2.5 trillion in 2000 and to US$5 trillion in 2006. This accelerated increase is part of the financial globalization process." [7].

In this context, Gross Domestic Product (GDP) as an indicator of economic performance and social progress becomes obsolete.

On the other hand, as sustainability becomes an increasingly critical question, it would be most interesting to substitute GDP with a *strong index* of sustainability, one that is affected by parameters linked to a quantitative definition of sustainability related to measures of the physical production of goods and services, combined with the existing indices of quality of life. These qualitative indices have already undergone detailed analysis and criticism by the Sarkozy Commision [4] and will not therefore be discussed in this present article.

To avoid market forces opposing a restructuring of productive sectors aimed at shifting from the present global economic model, which is unsustainable, to a sustainable model, using renewable sources of energy available on our planet, it would be necessary the establishment of aggregate national accounting of input (and waste) flows used (and generated) not only by productive processes, but also by consumption and final disposal of waste. These Material Flow Accounts must be based on the masses of physical inputs and outputs of productive processes [8]. The materials with a greater entropic (environmental) impact must be included in the flow with a greater weighting. For example, the impact of a kilogram of aluminium is much greater than that of a kilogram of timber.

3. Entropic impacts as baseline for a quantitative definition of sustainablility

In order to outline a quantitative definition of sustainable economic performance we have to organize different human actions, projects and undertakings with one common goal in mind (to produce food, build homes, transport people, etc.) according to the magnitude of their environmental impacts. This can be based on certain fundamental concepts of thermodynamics, as laid out below.

Systems that exchange neither energy nor matter with their surroundings are said to be isolated. Systems that exchange energy, but not matter with their surroundings are referred to as closed systems, while Systems where there can be an exchange of both energy and matter with the external environment are known as open systems.

The first law of thermodynamics, or the law of conservation of energy, determines that the internal energy of isolated systems remains constant and they are, therefore, always in a steady state.

The second law, in its most general form, states that in any interaction of a system with an external environment, or its internal processes (even in the case of isolated systems), the entropy of the system never diminishes. In fact, in the case of isolated systems, macroscopic irreversibility is one of the preferred forms of expressing the second law: *The entropy of an isolated system never decreases.* In other words, in isolated systems, the entropy continues to grow until it reaches a maximum value, a value referred to as thermodynamic equilibrium.

Open systems can also remain in a steady state, receiving (or emitting) energy, and matter, from external sources and discarding (or receiving) the same quantity of energy received (or emitted), and the added (or reduced) entropy to (or from) their exteriors.

We now consider two states of equilibrium of a closed system, located in the neighborhood of the radius $\varepsilon \to 0$ and we designate their entropies as $S(A)$ and $S(B)$.

In a reversible process, the entropy variation between these two states is the quotient between the quantity of energy transferred during the passing from one state to the other (dQ), and the absolute temperature (T), that is, $dS = dQ/T$. Therefore:

$$S(B) - S(A) = \int_A^B \frac{dQ}{T} \tag{1}$$

Since the first law of thermodynamics states that the total energy of an isolated system should be conserved, and the second law establishes the restriction that the entropy does not diminish, one can deduce that, in isolated systems, the free energy is gradually degraded and produces entropy until it reaches a state of equilibrium, of maximum entropy, which is maintained. In other words, gains in entropy imply transitions to more probable states.

The system Earth is not isolated, just as the subsystems that form it are not, as they all exchange energy and matter with the systems that surround them.

Earth is an open system, one that remains in a steady state thanks to its permanent contact with an external source of energy, the radiation emitted by the Sun. In fact, Earth is a dissipative system that exchanges energy and matter with the universe since it receives radiation (and meteorites) and emits radiation. Systems with these characteristics are said to be in *thermodynamic non-equilibrium* and, in their case, the second law of thermodynamics takes the form of a continuity equation that governs the exchange of energy of a variety of entropies across their borders.

This equation puts the variation of the system's entropy in the form of an increment of entropy internally to it, added to the net flow of entropy that crosses its borders, that is, $dS/dT = dS_{int}/dT + dS_{ext}/dT$, where dS/dT is the variation of the system's entropy; dS_{int} is the algebraic sum of the variations in entropy of the various subsystems that make up the system in question, and dS_{ext}/dT is the net flow of entropy that crosses its borders [9].

The form of energy predominant in the Universe is gravitational energy. Basically, it is gravitational energy that determines the direction of the general flow of energy within the Universe, not only because it is predominant, but also because it has maximum quality, that is, it is not degraded. Every piece of matter that exists in space possesses gravitational energy which can be released in the form of light and heat through the gravitational collapse of matter. Opposing this collapse are certain barriers such as, and especially, the dimensions of the Universe itself, since gravity is inversely proportional to the square of these dimensions. The energy resulting from the rotation of the galaxies is also one of these barriers. In the case of the stars, the main barrier to gravitational collapse comes in the form of nuclear reactions that occur inside them [10].

In other words, the stars (including our Sun) are nuclear fusion reactors contained within "gravitational containment vessels". Under gravitational pull, the density at the centre of the Sun is $150\,g/cm^3$ and the temperature is in the region of 1.5×10^7 K. The energy being emitted by it has its origins in the proton-proton cycle, with a reaction of the kind $p + p \to {}^2H$ + neutrino, followed by ${}^2H$ + proton $\to {}^3He$ + photon and of others, until it reaches $2p + 2e^- \to {}^4He$ + 2 neutrinos + 27 MeV, which is, on average, the energy released per reaction [11].

The main source of energy on Earth is made up of high-energy photons that result from reactions of this kind, which occur in the Sun and arrive on Earth by means of a low entropy flow.

Among many other things, the energy emitted by the Sun is responsible for photosynthesis, which allows plants to grow. These plants then in turn, directly or indirectly, provide us with biofuels and fossil fuels.

The radiation emitted by the Sun is at the same temperature as its surface, which is in the region of 5760 K.

Outside the Earth's orbit, the flow of solar radiation ("yellow photons", with low entropy) reaches the edge of the atmosphere at a temperature of 5760 K and, in passing Earth, begins to degrade through diabatic processes, that is, ones that are diathermic and diffusive, until they drop to the temperature level of the radiation emitted by Earth into space. The degradation of energy through terrestrial processes implies the production of entropy and establishes the direction of all the processes that occur on our planet.

In order to remain in a steady state (with the energy balance stabilized) Earth has to resend into space the same amount of energy it has received from the Sun.

If we assume that Earth is a black body at a temperature T_{earth}, the energy balance of the process in steady state can be modeled using the following expression:

$$\frac{I_0}{A}(1 - \alpha_E) - \sigma_B T_{earth}^4 = 0 \tag{2}$$

where I_0 is the solar flow in Earth's orbit, outside its atmosphere, or solar constant ($1367\,W/m^2$); α_E is the terrestrial albedo (~0.30); σ_B is the Stefan–Bolzmann constant ($5.67 \times 10^{-8}\,W/m^2/K^4$); T_{earth} is the radiation temperature emitted isotropically by Earth.

Solving for the temperature T_{earth}, we have a final terrestrial radiation temperature emitted into space of:

$$T_{earth} = (41.88 \times 10^8)^{1/4} \approx 255\,K \tag{3}$$

Therefore, the energy emitted isotropically by Earth ("red" photons, with high entropy) is at a temperature that is only around 1/20 of the temperature of the incident solar flow.

The fact is that Earth is not a black body and, according to measurements carried out in metrological stations around the world, including in both polar and tropical regions, the average temperature of the atmosphere is nearer to around 288 K, or 15 °C.

Fig. 1 shows a simplified model of this process.

The difference between the temperature of terrestrial radiation emissions into space and the temperature of the atmosphere is, therefore, 288 – 255 K = 33 K and is due to the greenhouse effect. Much below or above 288 K would make human existence unsustainable.

Given the present composition of Earth's atmosphere, water vapour accounts for 2/3 of the greenhouse effect, in other words, for 22 K. The great part of the remainder comes from CO_2 (8–9 K), while gases such as CH_4, N_2O, O_3 and the chlorofluorocarbons of an anthropic nature contribute with something like 2–3 K [12].

We showed earlier that solar photons reach the outer edge of the atmosphere with high energy levels (frequencies of around 7.5×10^{14} Hz) and a temperature in the region of 5760 K and are then irradiated isotropically by Earth with low energy levels (frequencies of around 0.38×10^{14} Hz), and a temperature of approximately 255 K.

Since the energy of a photon is equal to $h\upsilon$ (where h is Planck's constant and υ is the frequency of the photon being considered), in order for a flow of high energy photons to be balanced by low energy emissions, the difference in energy of the photons needs to be compensated for by their number. Thus, the number of photons sent by Earth into space should be around 20 times greater than the number of photons it receives from the Sun.

If the Earth did not exist, these solar photons would follow their own path as normal. The Sun–Earth duo is, therefore, a creator (or multiplier) of entropy. Figuratively speaking, the price paid by Earth and other planets to maintain themselves in a steady state comes in the form of a contribution to the increase of entropy in the Universe.

According to the Standard Model, 10 s after the Big Bang, some 15 billion years ago, the temperature of the Universe was in the order of 3.9×10^9 K. Seven-hundred thousand years later it was

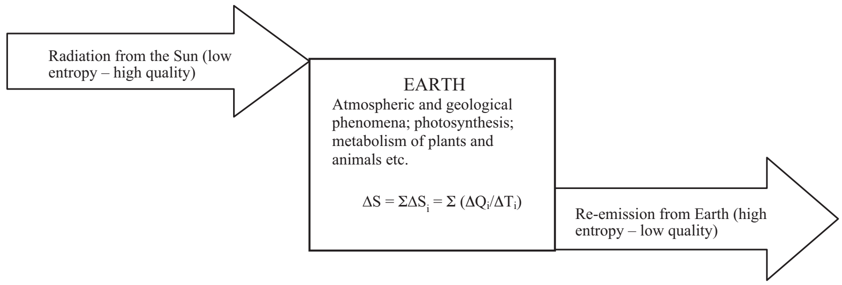

Fig. 1. Earth as an open system in thermodynamic non-equilibrium and steady state.

3000 K, and it continued to drop more gradually until it reached around 3 K, the present temperature of background radiation [13]. Astronomers and cosmologists calculate that, in another 15 billion years, the temperature of the Universe will probably have dropped to somewhere around 1.5 K [13].

Every phenomenon that occurs on Earth and on other planets contributes to the increase in the entropy of the Universe, as a result of the degradation of high quality energy (low entropy) into forms of low quality energy (high entropy) that become ever less usable. It is this that takes us naturally to the idea of final equilibrium – or "the thermal death of the Universe" – a point when maximum entropy is reached.

On a human temporal scale, which is what we are interested in this article, it was thanks to this very thermal non-equilibrium between Earth's atmosphere and the Universe that gradients of potential emerged favouring the formation of a biosphere, and in turn allowed for the gradual birth of successive forms of life, from the eukaryotes to *Homo sapiens* [14].

As already mentioned above, on its way past Earth, incident solar energy gradually becomes degraded through various processes associated with temperature gradients.

In order to calculate the net flow of entropy discarded by Earth into space we can integrate the expression $dS = dQ/T$, remembering that T is the temperature of the source that provided the quantity of heat dQ to the system. One should note that this temperature is not necessarily equal to that of the system that receives the heat, but can be equal to that of a part (or sub-system) of it, which is in direct contact with the source of the heat [15]. Thus, the solar energy that arrives at the outer edge of the atmosphere at a temperature of 5760 K is degraded through various terrestrial processes and then returned isotropically to space at a temperature of 255 K. Earth, therefore, sends out into space a flow of entropy $S = Q(1/T_{earth} - 1/T_{sun})$, where Q is the quantity of energy that arrives at Earth and is reemitted into space:

$$Q = \frac{I_0}{4}(1 - \alpha_T) \tag{4}$$

In dealing with diabatic processes, one cannot directly measure their contributions to global production of entropy by the Earth system. We can, however, evaluate, in approximate terms, the contributions made by each one – based on the flows of energy and on estimates of the temperature bands in which each process occurs. For example, diabatic heating, which is the main forcing of global atmospheric circulation, can be estimated using parameters of the physical processes involved, such as radiation flows, release of latent heat of condensation; exchange of heat between the atmosphere and the surface, etc. The global hydrological cycle is due to the evaporation of water from hot oceanic surfaces (and evapotranspiration of forests), to cold non-saturated atmospheres, with the subsequent condensation at colder temperatures and precipitation consuming energy and producing entropy [16].

Not all the high energy photons that come from the Sun are degraded immediately into low energy photons. A fraction of them is retained by means of photosynthetic reactions that "store" them in living organisms, in the biosphere.

The energy that is stored is equivalent to the difference between the chemical energy contained in the synthesized organic compounds (and in the oxygen released), and that contained in the carbon dioxide and the water in the atmosphere that feed photosynthesis. This energy can be estimated in terms of the variation of the free energy in the process.

In order to maintain its metabolism and carry out the work of reproduction, growth and movement, every living being depends on a source of free energy.

A food chain is a sequence of processes whereby plants are formed through photosynthesis. Herbivore animals eat these plants and in turn are transformed into food for carnivores, thereby preventing a fraction of solar photons from being degraded immediately in their passing through Earth.

It is interesting to remember that in February of 1943, at the conference entitled "What is Life?", held at Trinity College, Dublin, Schrödinger opened up new horizons in the fields of biology and genetics when he showed that life maintains order by degrading free energy and producing high entropy waste [17]. The free energy he was referring to can therefore be found in the natural environment and is, directly or indirectly, the result of photosynthesis.

Besides direct solar radiation and in addition to bioenergetic sources, the Earth's environment also offers geothermal and gravitational energy sources.

We also have uranium and thorium, which have remained preserved within the Earth's crust thanks to the powerful force of the surface tension of their nuclei.

In Eq. (1) the integral was taken over a reversible transformation between two states of equilibrium. In an irreversible transformation, the following inequality then prevails:

$$S(B) - S(A) > \int_A^B \frac{dQ}{T} \tag{5}$$

The entropy function, S is monotonically increasing in relation to Q because, in transferring heat to any system, the thermal movement of the atoms that form it intensifies.

This is equivalent to increasing the chaos in the distribution of these atoms, as per the various states of their microscopic movement.

It is impossible to describe the behaviour of each micro-system of a system (or of each atom of a compound), but, by using statistical mechanics tools it is possible to quantitatively characterize the thermodynamic state of this system, by means of the number of micro-states that define it. This number represents a statistical weight, or probability, of the thermodynamic state in question. A well-organized system tends to fragment itself into many parts. Any system left to itself tends to move to a more probable state, or one with a greater statistical weighting – or with more entropy. In other words, the entropy of a system is directly proportional to the number of its elements. In effect, the number of indications needed

to describe an elementary object is lower than is needed to describe an object made up of many elements.

Based on a study of the kinetic-molecular behaviour of gases in isolated systems, Bolzmann showed the existence of a functional relationship between the logarithm of the number that indicates the probability of the state of a micro-system, and its entropy, defined by the classic expression $S = k \times \ln \pi$, where S is the entropy, k is the Bolzmann constant and π is the said probability. Probability Π that a system that consists of n micro-systems is in a state Ω, is equal to the product of probabilities π_1 and $\pi_2 \cdots \pi_n$ that each one of these micro-systems is in a state that contributes to the composite system being in state Ω, in other words, $\Pi = \pi_1 \times \pi_2 \times \cdots \times \pi_n$.

Therefore, the entropy of the system composed of the n mentioned subsystems would be:

$$S = k \ln \Pi = k \ln(\pi_1 \times \pi_2 \times \cdots \times \pi_n) = k \ln \pi_1 + k \ln \pi_2 + \cdots + k \ln \pi_n = S_1 + S_2 + \cdots + S_n$$

This is trivial and can be generalized so that the variations of entropy have an extensive property, that is, the order of a system made up of **n** micro-systems varies according to the sum of the variations of the orders of these micro-systems:

$$\Delta S = \sum_{i=1}^{n} \Delta S_i \qquad (6)$$

One should note that the Bolzmann argument is strictly valid for gaseous systems and other micro-canonical collectives, that is, isolated systems whose parts practically only interact sufficiently in order to establish thermodynamic equilibrium.

In canonical collectives (that include liquid systems and systems in the gas–liquid transition phase), as in the Shanon Information Theory and its reformulation by Jaynes, entropy is defined as the lack of information on the state of a system, expressed as the *average value* of the logarithm of the number that indicates its probability.

In the formulation of mathematicians Kolmogorov and Sinaï, entropy is the asymptotic rate of information creation (or destruction) by means of iteration, in time **t**, of an isomorphism with a compact nucleus that has its dimension preserved [18].

As upshot of deeper theoretical research, this formulation could be used in the mathematical modelling of the behaviour of natural ecosystems that are submitted to external interference, which destroys their biodiversity (consolidated in genetic and other information) and causes a drop in their resilience levels. Such losses of information would take the form of gains in entropy and, symmetrically, in regenerating, these ecosystems would lose entropy.

In systems that are in thermodynamic non-equilibrium, the production of entropy in diabatic processes obeys the principles of minimum or maximum entropy production, according to the respective boundary conditions and degrees of freedom.

For systems close to thermodynamic equilibrium, Prigogine introduced, in 1962, the principle of minimum production of entropy, according to which the steady state is associated with the minimum production of entropy inside the system [24].

Degradation of energy through biological phenomena, that is, photosynthesis, metabolism and reproduction, etc., obey the principle of minimum production of entropy, as well as in certain localized anthropic processes, such as economic activities, that is, processes that occur in industrial, agricultural and service sector industries [19,20]. In any one of these processes Eq. (6) remains valid.

We stated previously that the entropy of a system is proportional to the number of elements that it is composed of. Hence, when one extracts a material from the ground that had been “organized” into molecules under the general formula C_nH_{2n+2} and others that are equally “well organized”, and burns it in an industrial installation or in an automobile, then one causes its “disorganization”, fragmenting it and multiplying it into molecules of flue gases and a variety of particulates.

The burning of a hydrocarbon material resulting from the fossilization of remnants of algae and other organisms, formed through photosynthesis hundreds of millions of years previously, contributes to an increase in the entropy of Earth in an amount equivalent to the entropy that had been **contained** all that time ago when the organisms formed through photosynthesis and created the material in question. As small as this increase in entropy might be, it nevertheless takes us in the opposite direction to that of maintaining our planet in a steady and sustainable state.

The nuclear fuel cycle, which begins with the mining and concentration of uranium oxide, passes through the conversion and enrichment process and ends up with the release of binding energy of ^{235}U atoms, through their fission into lighter elements, also “disorganizes” organized material and produces entropy.

In another context, this also occurs when information is lost through the destruction (or “disorganization”) of the biodiversity of a natural ecosystem, as seen above.

In 1957, working on the principles of statistical mechanics of systems in equilibrium, on which the Bolzmann and Gibbs entropy definition is based, Jaynes made relevant contributions to the statistical mechanics of systems in non-equilibrium (*Non-Equilibrium Statistical Mechanics – NESM*), on which the principle of maximum entropy production (*MaxEP* or *MEP*) is based: “A system will select the path, or assemblage of paths out of available paths that minimizes the potential, or maximizes the entropy, at the fastest rate given the constraints”.

The validity of this principle was evidenced in an empirical form and, in recent years, Garth Paltridge, Roderick Dewar, Hisashi Osawa, Atsumu Ohmura, Ralph Lorenz and others have provided theoretical demonstrations of it.

This principle implies that systems that are far from a thermodynamic equilibrium remain in a steady state, with maximum entropy production [21].

Diabatic heating, which causes the transfer of heat from the tropics to the poles, is a process with many degrees of freedom associated with atmospheric circulation and the temperature gradients between the Equator and the poles. These are at temperatures that depend on localized energy balances, which are in turn affected by the amount of heat being transferred.

The global hydrological cycle is due to the evaporation of water from hot oceanic surfaces (and the evapotranspiration of forests) to colder non-saturated atmospheres, with the subsequent condensation at lower temperatures and precipitation consuming energy and producing entropy. These macro-phenomena generate a chaotic behaviour that implies maximum entropy production on the part of the Earth system.

Both processes that imply minimum and maximum entropy production contribute to the stabilization of Earth’s energy balance and to the preservation of the gradients that ensure life and establish the general direction of all the processes that occur on our planet.

Thanks to this, the Earth system remains in a steady state.

Of the fundamentals mentioned above we should keep in mind the following:

- The principal source of energy on Earth is the Sun, which is essentially a nuclear fusion reactor contained within a “gravitational containment vessel”.
- The entropy increases in relation to the energy because, in transferring heat to any system, the thermal movement of the atoms that form it intensifies. This is equivalent to say that the entropy that indicates the degree of disorder associated with a form of

energy varies inversely with the temperature associated with that form of energy. As there is no temperature associated to gravitation, gravitational pull does not produce entropy.

- Life is maintained as a result of gradients that induce the degradation of high quality energy. These gradients exist because the algebraic sum of the flows of entropy produced in terrestrial subsystems remains stable and Earth releases entropy into the Universe. Therefore, in order for life to be maintained, the sum of the flows of entropy of Earth's various subsystems should not differ significantly from present levels.
- The entropy of a system depends on the number of its elements and on the series of information needed for its thermodynamic equilibrium. Any process that disorganizes or destroys information, or reduces the efficiency of a system increases its entropy.
- The present concentration of CO_2 is responsible for around 8–9 K of atmospheric warming. Increases in this concentration will intensify the greenhouse effect and alter the gradients that ensure life exists on our planet.

One can, therefore, define sustainable development, in light of the intensity of environmental impacts caused by economic activities, as that which tends to maintain the sum of flows of the entropy production of terrestrial systems at close to present-day levels, as it is these that ensure life exists on Earth.

> Sustainable development is that which does not contribute to the deviation of the sum of flows of the entropy production of terrestrial systems from present-day levels.

This definition is still not precise. However, based on it, we can establish in an approximate, albeit logical form, scales for the magnitude of the impacts on the natural environment caused by basic economic activities.

For the time being, these scales are limited by the lack of experimental work and by the insufficiency of quantitative data. However, as interest in this subject grows, so researchers in energy technology and energy planning will be able to define ever more precise scales for what we can call the *Entropic Grading* of the activities under consideration: higher entropies imply greater "disorder", hence they cause more intense impacts.

Thus, energy sources that have less impact should receive lower *Entropic Gradings*.

One will, therefore, be able to grade the main *production chains* by their *Entropic Gradings* and the intensity of their respective environmental impacts.

All production chains (industrial, agricultural and service sector) consume energy and, therefore, they all begin with one primary source of energy:

Primary energy → Useful energy → Extraction, transport and processing of raw materials → Industrial production → Transport and distribution of finished products. . .

As an example, let us construct a provisional table, listing the energy cycles used in basic economic activities based on the intensity of their environmental impacts.

Beginning with electricity, the cycle will proceed alternatively from a hydroelectric, fossil, wind, photosynthetic, photovoltaic, or nuclear source.

We will grade these sources, beginning with, let us say, Grade 1 and going up to, let us say, Grade 10, taking into account the entropic impact that results from the exploitation of a primary energy source to the operation of an electric power plant. For instance, the nuclear thermoelectric plant also takes into account the impact of the nuclear fuel cycle, which begins with the consumption of oil derivatives during the extraction of uranium mineral, and so on.

Table 1
Entropic grading of electricity generating plants, on a scale of 1–10.

Generation plants and primary sources	Entropic grading*	Intensity of impact
Fossil fuel-run thermoelectric plants	10	
....	?	
Nuclear thermoelectric plants	?	
....	?	
Biofuel-run thermoelectric plants	?	
....	?	
Geothermal plants	1	
Wind turbines	1	
Photovoltaic and thermo solar systems	1	
Hydroelectric and tidal power plants**	1	

* Depending on the manner of exploitation, may insert and receive other grades.
** Gravitational.

On the other hand, there is no temperature associated to gravitation, and therefore gravitational pull does not produce entropy. Since hydroelectric energy comes from masses of water that are attracted to the centre of the Earth by gravitational pull, clearly this primary source should be given a minimum grade in the Entropic Grading (Grade 1).

Starting with this as the baseline and remembering that present-day levels of entropy ensure existence of life on Earth, we will grade other sources. This will require innumerous theoretical studies, as well as the respective investments in the experimental field, in order to ensure that we have a reliable database on which to work on. However, we can already establish approximate grading of the impacts on the natural environment caused by energy sources and plants. Table 1 shows an outline of this kind of grading.

Let us now consider an investment in electric energy generation on a large scale. In practice, the alternatives presently available are hydroelectric, fossil fuel-run thermoelectric, nuclear, wind and biofuel-run thermoelectric plants. The goal of the project (supply consumers with electricity) must be achieved through investment in the alternative that will cause the minimum impact, which effectively means the least disorder in the environment, or minimum increase in entropy. In this case, the decision should favour the hydroelectric plant, which has the lowest *Entropic Grade*.

If the region in question does not possess the necessary conditions for exploiting hydroelectric power then the second best option of choice should be an interconnecting system, made up of photovoltaic plants, wind turbines and biofuel-run thermoelectric plants, and so on.

In current terms one could say that any process that disorganizes, destroys information or reduces the efficiency of a system increases its entropy, that is, degrades the quality of its energy due to reasons such as: friction, in mechanical systems; electrical resistance, in electrical systems; turbulence, viscosity, etc., in fluid systems; noise, in electronic systems; over-exploitation, bad use of the soil and poor logistics, in agricultural systems; chaotic transport and energy wastage, in cities; bureaucracy, in administrative systems, etc.

Inversely, processes that draw on high quality energy from one system in order to increase order in another system, reduce the entropy of this other system, at a cost of increasing the entropy of the system from which high quality energy was drawn upon.

When we have sufficient multidisciplinary studies on the subject then tables can be organized on more precise foundations, for purposes such as producing foodstuffs, running transport networks, lighting and climatizing environments, generating process heat, etc. For the time being, however, we are limited by the lack of quantitative data [20], and as a consequence there is still much interdisciplinary work to be done, uniting R&D efforts in

the fields of chemical, mechanical and electrical engineering, agricultural sciences, ecology, economics and social sciences among others.

At a later stage, it may be possible to variegate alternatives to the same project, in light of the possible forms of exploitation and respective entropic grading. We can use as an example the main obstacle to the transition of the unsustainable model (dependent on fossil fuels) to a renewable model. This obstacle can be found in the transport sector, where high density energy fuels (gasoline, kerosene, diesel, etc.) are indispensable.

Biomass fuels are less entropic than oil derivatives, but this statement should be put into context. It is true that the main biofuel presently in use (ethanol) is obtained through the fermentation of plant biomass through a process that uses enzymes to unleash reactions, but there is a new generation of biofuels being developed in the United States, which are obtained through catalytic reactions, at temperatures that are much higher than those of fermentation processes [22]. These biofuels have a much higher energy density than ethanol and open the way up to a large proportion of that country's demand for oil derivatives eventually being substituted by renewable fuels. The Americans hope that these biofuels will be ready for licensing by 2011 [23]. Their production is more efficient and their entropic impact is lower than that of ethanol.

When these fuels are ready for use, it will be possible to establish their entropic grading thanks to the planting methods and the products and techniques used in the base planting for these fuels.

One will be able to list different systems of transport according to their entropic impacts, depending on the type of energy they use.

Another example would be traditional buildings, climatized and lit by electricity intensive systems that cause much more serious environmental impact than buildings projected and built on the basis of bioclimatic and photovoltaic architectural projects.

Yet another example would be a chaotic and congested city that provokes much greater impacts than well-organized conurbations.

4. Final remarks and conclusion

The production of entropy may serve to mark out the gradual restructuring of productive systems, so that the economy as a whole can gradually come closer to sustainability. However, much still has to be invested in R&D, in order to create the database needed to be able to assess the production of entropy in a wide range of economic activities.

Nevertheless, the production of entropy caused by the use of various forms of energy can already be estimated in approximate fashion, following a preliminary listing as outlined in Table 1.

We could then outline the structure of an index that could be used to measure the physical production of goods and services, affected positively or negatively by parameters linked to sustainability and the quality of life. One would have, therefore, a *Sustainable Human Development Index (SHDI)* that would be a direct function of an index structured on the basis of the existing statistical indicators of human development, improved in accordance with the studies of the Sarkozy Commission (let us say, the *Cmesp Index*, or *CMESPI*) and affected by parameters linked to a quantitative definition of sustainability, which would in turn be set by the entropic rankings of the products with greater weightings in the production of the economy, and brought together in the form of an Environmental Sustainability Index (say, the *ESI*).

The SHDI of a country would, therefore, be a function of its CMESPI and ESI indices that is:

$$\mathrm{SHDI} = f(\mathrm{CMESPI}, \mathrm{ESI})$$

In order to enable this index to generate practical results, the WTO (World Trade Organization) could establish a scale of increments, to be applied to tariffs on products originating in countries in different indexes.

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